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Multi-Flight Condition Optimization of Three Dimensional Supersonic Inlets

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This paper presents an innovative methodology to address the three-dimensional supersonic inlet design problem. An efficient and robust process allows to optimize the aerodynamic performance of inlets for multiple flight conditions. This optimization process links together an optimizer with a fast and accurate simulation tool into an automated optimization loop. The implementation of this new design technique and its applications to two different test cases are presented, namely, the optimization for a single cruise condition, and the optimization for a mission comprised of acceleration, cruise and maneuver phases. The mission-optimized inlet achieves better overall performance than the cruise-optimized inlet.

1 Introduction

The design of high speed inlets for supersonic vehicles is an intricate exercise and a challenging issue. The classical design process mainly relies on engineers' experience and on the limited human capability to cope with a large number of coupled parameters. As a consequence, the design process can be long, laborious and extremely expensive, without any guarantee to lead to the best performing design. In that context, taking into account the progress accomplished in both numerical flowfield simulation and artificial intelligence domains, automated design process strategies appear to be an appropriate answer to the inlet design problem. Actually, the association of efficient optimization algorithms and fast aerodynamic performance analysis tools has proved to be able to give better designs than classical design methods, while reducing the time cost.

Optimizations have already been carried out successfully for several two-dimensional problems. Hussaini et al.[1] and Borivikov et al.[2] have worked on two-dimensional nozzles. Several studies have dealt with two-dimensional supersonic and hypersonic inlets. Zha *et al*[3] and Shukla *et al*[4] performed optimizations of two-dimensional supersonic missile inlets.

Wind tunnel experiments as well as Reynolds Averaged Navier-Stokes (RANS) calculations have shown that the flowfield through supersonic missile inlets is highly three-dimensional,[5] even for inlets with rectangular cross-section under symmetric free stream conditions. Moreover, since the vehicle has to fly an entire mission, the inlets experience very different inflow conditions throughout this mission and its multiple flight conditions. Thus a methodology for inlet optimization which accounts for both the three dimensional feature of the flow field and the different flight conditions met through the mission of the vehicle is clearly needed.

The research presented in this paper describes an efficient and powerful tool to optimize the aerodynamic performance of a full three-dimensional supersonic inlet for a complete, realistic mission. An important issue is the cost of the performance evaluation of such three-dimensional systems, especially when the entire mission is considered, since it leads to several analysis, one for each flight condition. A full RANS simulation of a three-dimensional inlet typically requires several hundred CPU hours on a workstation. While this cpu requirement permits RANS simulations to be used in a manual design process (where only a few designs are

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considered), it precludes the use of RANS simulations as the basis of an automated design process which requires hundreds of flowfield simulations. Therefore, a hybrid flow solver based upon an innovative combination of an Euler flow-solver and a one-dimensional subsonic diffuser model has been developed. The simulation time with this tool has been reduced to few CPU minutes, allowing the current automated design optimizations.

After describing the problem addressed by the present study, the optimization methodology and the different elements involved are described. Then the results for both a single flight condition and a full mission optimizations are presented and analysed.

2 The Problem of Multi-Flight-Condition Optimization of a Generic Supersonic Inlet

2.1 Overview

The problem is the design of three-dimensional supersonic missile inlet. The function of a supersonic inlet is to capture supersonic flow and efficiently decelerate it in order to provide the engine with a sufficient mass flow rate of high total pressure subsonic flow. This task is performed through three main stages presented in Figure 1.

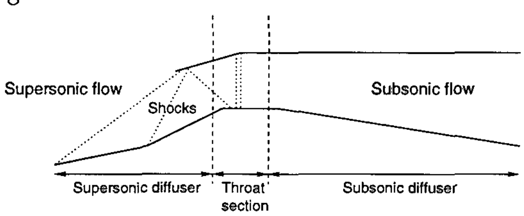

Fig. 1 Supersonic inlet critical operating regime

First, a set of oblique shocks forms in the supersonic part of the inlet and decelerates the supersonic incoming flow. Then a terminal shock system (an approximate normal shock) occurs in the vicinity of the geometrical throat. Finally, the flow is further decelerated in a subsonic diffuser.

To achieve high performance, the inlet design must be optimized for the flight condition according to a set of constraints imposed by manufacturing considerations and engine specifications. But through the entire mission the air-breathing vehicle has to fly, the inlet faces several flight condition which can be very different. Therefore the generic inlet optimization problem can be defined as the maximization of the inlet aerodynamic performance for an entire mission, within a space of feasible designs which corresponds to the given set of constraints imposed on the inlet.

2.2 The Single-Flight-Condition Optimization

Given a particular flight-condition, *i.e.,* a particular inflow condition, two main coefficients are used to assess the aerodynamic performance of the inlet in this condition. The total pressure recovery coefficient η is representative of the efficiency of the flow deceleration performed by the inlet. It is defined as

$$\eta = Pt_{exit}/Pt_0$$

where Pt_{exit} and Pt_0 are respectively the averaged total pressure in the exit plane of the subsonic diffuser and the freestream total pressure.

The mass flow rate coefficient ε represents the relative amount of flow captured by the inlet and is defined as

$$\varepsilon = \frac{\text{mass flow entering inlet}}{\text{maximum mass flow at } \alpha = 0^\circ \text{ and } \beta = 0^\circ}$$

where α and β are the angles of attack and sideslip, respectively.

Therefore, the problem of the inlet optimization for this particular flight condition can be formulated as the search for the global optimum

$$\begin{gathered}\text{maximize } \eta(\mathcal{G})\\ \text{subject to constraints}\end{gathered}$$

where $\mathcal{G}$ represents the family of feasible geometries. One of the constraints imposed for the inlet design is to achieve a sufficient mass flow rate coefficient ε.

2.3 The Mission Optimization

Overview

As pointed out previously there is a strong need for the inlet to be optimized not only for one particular flight-condition, but rather for a full mission. The mission, from the point of view of the inlet performance, can be seen as a succession of flight conditions (or flight points).

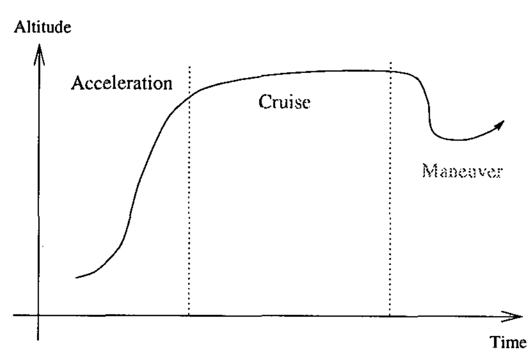

Fig. 2 Profile of a mission

Although this succession is continuous through the mission, this mission can generally be discretised into several stages. Figure 2 represents a typical mission profile. Three different stages are often considered to

define the mission. The first stage is the *acceleration*. It begins at the self-start Mach number of the inlet, which is actually a design parameter (the boost phase is not considered here). During this acceleration stage, the missile has to accelerate and climb to reach its cruise altitude and speed and therefore needs a high thrust. This requirement also implies a high mass flow rate coefficient. At this point, the total pressure recovery is generally high but it is nevertheless important to maximize it. The second stage is the *cruise*. Here, the missile is required to fly the longest distance as possible. Therefore, the fuel consumption is of primary interest and so the total pressure recovery must be maximized. As the missile gets closer to its target, it enters the *maneuver* stage. At this point of the mission, the primary parameter is again the total pressure recovery which must be maximized while the mass flow rate has to be larger than a specified minimum value.

In summary, the mission can be discretised into three different stages which can be considered independently. The total pressure recovery has to be maximized for all the mission stages, while the mass flow rate must be kept larger than a minimum value specified at each stage.

Optimization Strategy

Since the mission yields three different stages, the problem which has to be considered is now multi-objective since the η coefficient is to be maximized for each stage of the mission. But the total pressure recovery cannot be maximized independently for each of the three mission points for a fixed inlet geometry, and the mission optimization is therefore a matter of compromise between the three mission points. The mission problem is handled through the use of a mission target curve for the total pressure recovery. This curve provides a target value for the total pressure recovery for each flight point in the mission. These target values are fixed according to the engine specifications and the mission requirements. However they are slightly overestimated in order to keep the total pressure value achieved by the optimal inlet below it. This target curve for the total pressure recovery will be denoted as $\eta_{target}(Mission\,Point)$. The different constraints applied to the inlet and especially the constraint on the mass-flow rate are also defined independently for each mission-point (See Table 4 in Section §4.2.2).

Given this definition of the mission, the goal of the optimization process is to minimize the gaps between the performance achieved by the candidate inlet on each point of the mission (η_i), and the target curve η_i^t. (See Figure 3). The actual values used to defined the target curve are given in Table 3 of Section §4.2.1.

Therefore the mission problem which will be addressed

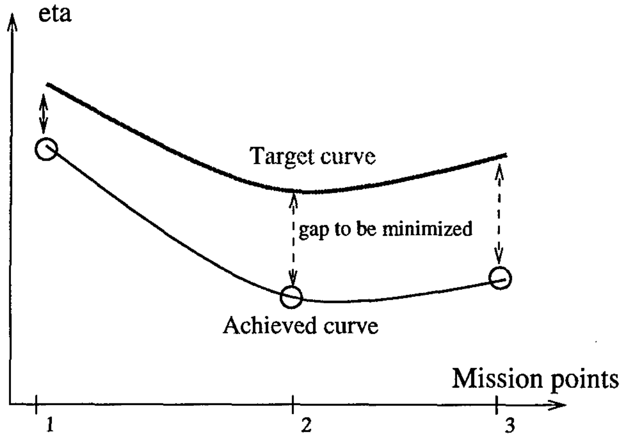

Fig. 3 Example of target and achieved curves

in the following can be expressed as

$$\begin{gathered}\text{minimize } \phi(\mathcal{G}) \\ \text{subject to constraints}\end{gathered} \tag{1}$$

where

$$\phi(\mathcal{G}) = \sum_{i \,\in\, \text{mission}} \left[\frac{\eta_i - \eta_i^t}{\eta_i^t}\right]^2$$

where η_i^t is the target value of η at mission point i.

2.4 Geometry Model of the Generic Inlet

Supersonic Part

The geometry investigated is a multi-ramp mixed compression inlet. The cross-section of the inlet is rectangular and the inlet can be considered as "two-dimensional". Nevertheless the three-dimensional features of the flowfield in such inlets have proved to be of considerable importance and are currently included in the simulation. A large amount of internal compression is provided by the cowl which is composed of four different segments, allowing to modify precisely its shapes.

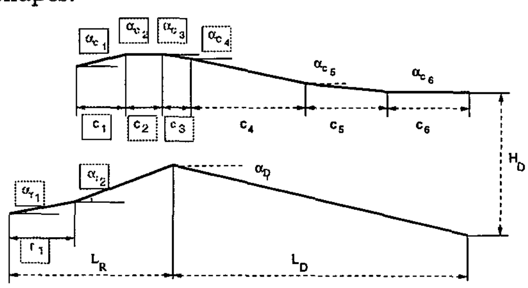

Fig. 4 2D parameters of the inlet

Subsonic Diffuser

A generic diffuser whose shape is fixed during optimizations is added to the supersonic part previously described, respecting some aerodynamic based design rules for its shape. The lower surface of this diffuser is kept flat, forming an angle of $-9.55°$ with the horizontal plane. The upper surface is composed of three equal length planes with increasing angle: $-8.55°$,

$-5.05°$ and $-0.55°$. These values of angle and length have been chosen to avoid separation and minimize the loss in the subsonic diffuser. The width of the diffuser is assumed to be constant.

This geometry model has been extrapolated from an experimental research performed by S.A. Fisher[6,7] and requires ten parameters to be completely defined. These parameters which describe the two-dimensional shape of the inlet are presented in Figure 4 where the ten design parameters are boxed. This parametrization of the inlet allows to investigate a large spectrum of three-dimensional shapes.

3 Methods Used in Optimal Design Process

3.1 Automated Design Loop

3.1.1 Presentation of the Optimization Loop

The innovative three-dimensional automated optimization process is based on the development of several tools linked within a loop algorithm presented in Figure 5. The optimization software which has been developed and used for the present research can use different optimization algorithms. The optimization has led to the development of a solver fast enough to allow a large number of calls and accurate enough so as to correctly predict the trends between investigated configurations. Outside of the loop, some verifications are made using full Reynolds-averaged Navier-Stokes simulations.

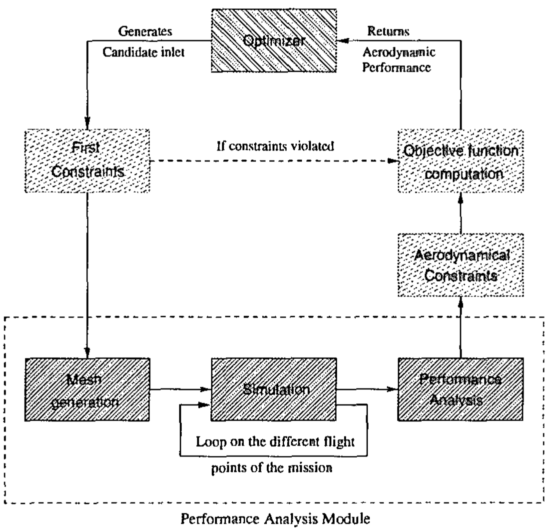

Fig. 5 Automated Optimization Loop

3.1.2 Automated Process Description

The heart of the optimization loop implemented for designing supersonic inlets is called the optimizer. The optimizer generates candidate inlet designs described by ten geometrical parameters (see Section §2.4). These parameters are passed to the analysis module which returns the aerodynamic performance of the candidate inlet. Based on these simulation results, the objective function and some aerodynamic constraints are calculated. In order to reduce the computational cost of the design process, geometry constraints are also implemented and checked before running the analysis module. If any of those constraints is violated, no evaluation is undertaken and the optimizer is simply given back a penalty for this candidate inlet based upon the amplitude of the constraint violation (see Figure 5). These features, which prevent from the evaluation of non-feasible inlets (from a physical point of view), save a significant amount of time during the optimization process, especially at the very begining.

3.2 Optimization Algorithm

The current optimization loop software is based upon the *Designer's Interface*, developed at Rutgers University. This optimization software includes different optimizers: GADO (a Genetic Algorithm), CFSQP (a gradient based search algorithm) and a random-probe algorithm and allow to choose easily any of this three optimization "engines". The *Designer's Interface* acts as an interface between the optimizer itself and the analysis part.

Previous optimizations[8] have demonstrated that the Genetic Algorithm GADO performs better than CFSQP for the particular problem of supersonic inlet optimizations. Therefore the present optimizations have been performed using GADO.

Presentation of GADO

GADO (Genetic Algorithm for Design Optimization) is a stochastic optimizer. It first generates a random population of potential candidates. Then mutations and recombinations are applied to individuals of the population in order to make the population evolve towards better solutions. GADO was developed by Khaled Rasheed[9] in the Department of Computer Sciences at Rutgers University. Compared to classical Genetic Algorithms, several improvements have been included that make the search more efficient and reliable for engineering problems.

Each individual is represented by a vector of real numbers, which is particularly well adapted to the parametric description of the inlet. Several innovative crossover and mutation operators have been developed in order to make the search process fast and accurate, *i.e.*, more likely to find the global optimum. Depending on the number of iterations allowed for the search, the stage of the optimization process is taken into account. For example, a guided crossover operator (which mimics a gradient-based method) is applied in the last part of the search, with a view to accelerate the convergence. The shape of the population is also

checked to detect premature clustering and a reseeding of the population can be performed in order the avoid the search process to be stuck near a local optimum of the design space. Finally, the penalty function has been tailored by the use of a penalty coefficient which increases during the process, so as to guide the search towards feasible regions.

This algorithm has already been used successfully for several different engineering test cases.[9–11] The advantage of this optimization tool is its ability to explore large parts of the design space and to reach the global optimum of topologically complex design space.

3.3 Inlet Performance Analysis Methodology

The accuracy and usability of any automated design process is mainly grounded on its performance estimation module. Indeed, the analysis part of the process must be accurate enough to predict the trend between candidate inlets and fast enough for the several hundreds of three-dimensional inlet analyses needed by the optimization to be performed within an acceptable time frame. To answer these requirements a hybrid flow solver, called 2ES3D (an acronym for Euler + Semi-Empirical Simulation 3-D), has been implemented to be used inside the optimization loop and validated.[12]

3.3.1 Simulation Overview

The compression which occurs in the inlet must be achieved with the minimum total pressure loss. Moreover, the engine requires a minimum amount of flow to be captured by the inlet to work in optimal conditions. Figure 1 describes the flow field in the inlet working in critical operating regime, *i.e.,* in the regime which leads to the theoretical maximum efficiency for the compression. First, a supersonic compression is performed through a series of oblique shocks. The flow remains supersonic until the throat region, where a shock system close to a normal shock occurs, downstream of the geometrical throat. After this shock system, the flow is subsonic and is compressed along a diverging duct which acts as a subsonic diffuser. Basically, total pressure losses occur across the various shocks and through the viscous effects in the subsonic diffuser.

The methodology developed for the aerodynamic performance evaluation is based on a physical analysis of the inlet operation (see Figure 1). 2ES3D first uses an Euler simulation to account for the supersonic compression occurring above the inlet ramps. Then corrections are applied for the loss through the terminal shock system and for the viscous losses through the subsonic diffuser. Figure 6 summarizes the different elements of the analysis process performed by 2ES3D.

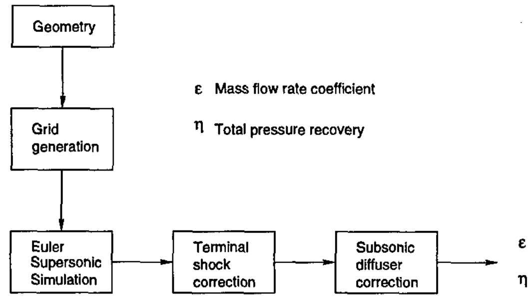

Fig. 6 2ES3D automated simulation process

3.3.2 Simulation Models

Euler Calculation

To compute the supersonic compression which occurs above the ramps and the associated losses through the different oblique shocks, an Euler calculation is performed using $\mathcal{GASP}$[13,14] Version 3.2 by AeroSoft, Inc. as the flow solver. In this respect, a grid of the inlet has to be generated. This grid is created with GridPro developed by Program Development Corporation.

The Euler simulation uses a third order accurate upwind scheme (Van Leer scheme) to compute the inviscid fluxes. A Jacobi scheme with inner iterations is used for relaxation. A tangential velocity boundary condition is applied on all the inlet walls and a supersonic outflow condition is used for the inlet exit plane.

$\mathcal{GASP}$ as well as GridPro are run automatically (without any user intervention) in batch mode.

Virtual Terminal Shock Model (VTS)

For the case of supersonic inlets, the main total pressure loss occurs through the terminal shock system previously described. At the critical operating regime, which is the one to be considered for optimization, the terminal shock is located in the vicinity of the aerodynamical throat which is a position known to be close to the geometrical throat or above the boundary layer bleed (if any). Nevertheless, in some cases a subsonic region occurs beneath the cowl which makes the terminal shock unlikely to be stabilized in the region where the flow is subsonic. In that case the terminal shock is applied just downstream of the subsonic area. Finally, the position where the terminal shock is placed is either the geometrical (if no subsonic zone is found) or the downstream position of the subsonic zone if such a subsonic zone exists. This methodology for positioning the terminal shock has proved to give results closer to reality than systematically applying it at the geometrical throat.[8]

This shock is modeled by taking into consideration each individual cell of the mesh at the chosen shock position and by applying the Rankine-Hugoniot formulae for this cell. An averaged value of the total pressure is computed behind the vertical shock. Then

the information about the flow just behind the vertical shock are passed to the one-dimensional subsonic diffuser model.

Subsonic Diffuser Model

The losses which occur in the subsonic diffuser are due to viscous effects. As the boundary layer develops with adverse pressure gradient due to compression, separation is likely to occur in the diffuser[15] , leading to strong reduction of the inlet performance. A one-dimensional model of the subsonic diffuser has been developed based upon a preliminary study done at Stanford University.[16,17] The inflow conditions used to initialize the computation are the averaged flow conditions found immediately behind the terminal shock. The flow field along the diffuser is calculated using a space marching strategy. A "weak-strong" method is applied when separation is detected to take into account the interactions between boundary layers and the non-viscous core flow. The velocity profile of Coles-Van Driest, corrected when boundary layer separate, is used to calculate the stress along the wall. Finally, the geometry of the diffuser is taken into consideration through the definition of its different wall-elements. This model, which is able to predict separation with a reasonable precision,[17] has turned out to be more accurate than empirical formulae for subsonic diffusers.

Bleed Implementation

Supersonic inlets usually incorporate a boundary layer bleed located in the throat region. The bleed role is twofold. Basically, it aims at removing the low energy fluid from the boundary layer which has developed on the supersonic compression ramps in order to prevent separation in the subsonic diffuser. Furthermore, it also helps to stabilize the terminal shock system close to the throat section (see Figure 1). In the present study, the bleed has not been taken into account for optimization, *i.e.*, in 2ES3D, since no boundary layer is computed in the Euler calculation performed by 2ES3D. This strategy is based on the assumption that, given an optimal inlet found with the present method, it is possible, *a posteriori*, to add to the optimal inlet a bleed which removes a sufficient amount of flow, so as to lead to an excellent final design. This assumption must be validated by performing RANS simulations of the optimal inlet design with bleed.

3.3.3 Validation of 2ES3D

A validation of three-dimensional inlet performance prediction using this method has been conducted,[12] pointing out its domain of validity and showing a 5% accuracy over this domain. The study has demonstrated that 2ES3D enables to correctly predict the trend in performance between inlet configurations. This is the most important feature for its use inside an optimization loop. Its reliability with regards to the mesh refinement for the Euler simulation has been tested and has shown a good agreement between fine, medium and coarse meshes. The accuracy of the Virtual Terminal Shock model for different positions of the terminal shock was also tested against Euler calculations with back-pressure. The final result is an efficient simulation tool for inlet performance which can accurately predict the trend between inlet configurations and allows important reduction in the computational resources needed for optimizations.

4 Results of Two Optimizations

4.1 Description of the Two Different Optimizations

Two different optimizations have been performed using the methodology and software presented in Section §3. The first optimization is a single flight condition optimization representative of a cruise stage. It served both to validate the automated design software and to provide a reference to assess the improvement obtained using the multi-flight conditions optimization concept. The second optimization is a mission optimization. The mission definition employed during this optimization re-uses the conditions of the first optimization for the cruise stage. The first optimizations intended therefore to provide the best performing inlet for the cruise stage, whereas the second optimization intended to yield a better compromise for flying the entire mission.

4.1.1 Aerodynamic Flight Condition for the Cruise

The first optimization was a single-flight-condition optimization. The inlet has been optimized for a cruise stage which is described in Table 1.

Flight Condition	Cruise
Mach number	3.2
Side-slip angle	0°
Angle of attack	4°
Altitude	12 km
Total pressure	955 kPa
Total temperature	660 K

Table 1 Aerodynamic conditions for cruise optimization

4.1.2 Aerodynamic Flight Conditions Used for the Mission

The second optimization was a multi-flight-condition (mission) optimization. As described previously, the mission was composed of three different stages. The specification of the three different mission stages are described in the Table 2 below. It has to be noted that

the cruise stage of this mission corresponds exactly to the flight-condition used in the first optimization for the single flight condition optimization.

Flight Cond.	Accel.	Cruise	Maneu.
Mach number	2.4	3.2	2.8
Side-slip angle	0°	0°	5°
Angle of attack	1°	4°	0°
Altitude	8 km	12 km	10 km
Total pressure	520 kPa	955 kPa	1306 kPa
Total temperature	508 K	660 K	680 K

Table 2 Aerodynamic conditions for mission optimization

4.1.3 Computer Environment

Both optimizations have been performed on Silicon Graphics R10000 processors. The single-flight-condition optimization took roughly 3.5 days of CPU time to be achieved, whereas the mission optimization took 14 days.

4.2 Settings Used for the Optimization: Objective and Constraint Function Definition

4.2.1 Objective Function

Single-Flight-Condition Optimization (Cruise)

The Genetic Algorithm GADO aims at minimizing the objective function. Since the targeted objective for the single-flight condition optimization is to optimize the total pressure recovery of the inlet, the objective function passed to the optimizer is $-\eta$, the negative value of the total pressure recovery.

Multiple-Flight-Conditions Optimization (Mission)

As it has already been described in Section §2.3, the objective of the mission optimization was to minimize the "gap" between the performance achieved by the inlet through the entire mission and the target performance for this particular mission. The definition of the target curve used for the present optimization is provided in Table 3.

Flight Cond.	Accel.	Cruise	Maneu.
Targeted η	0.8	0.6	0.65

Table 3 Mission optimization targets for η

The expression of the objective function for the mission optimization passed to GADO is Eq (1).

4.2.2 Constraints

The present optimizations are constrained, *i.e.,* the candidate inlet must meet a set of constraint to be considered as "feasible". The constraints intend to eliminate the designs which are not manufacturable, which do not self-start at the required Mach-number or which shapes are simply not-physical. Figure 7 presents the way these constraints are handled during the optimization process.

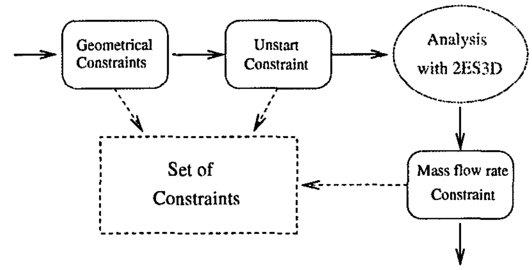

Fig. 7 Constraints verification process

Geometrical Constraints

Prior to the analysis code call, some geometrical constraints are checked, based on the ten geometry parameters passed by the optimizer. These constraints allow to eliminate, early in the process, unfeasible geometries according to manufacturing or physical considerations. This feature saves the time of a performance analysis with 2ES3D.

Unstart of the Inlet

Since the inlet is required to be self-started at a lower Mach number than any of the mission stages, a unstart criterion is applied, prior to the analysis code, to predict if the candidate inlet is started in the required condition. During the two present optimizations, the unstart constraint has been handled using an approximate criterion.

First, the Mach number value at the cowl entrance is computed using Rankine-Hugoniot formulae and taking into account only the two-dimensional geometry of the inlet. Then, the actual contraction ratio, define as $(Entrance\ Cowl\ Section\ Area)/(Throat\ Section\ Area)$, is compared to the maximum contraction ratio which would allow a Pitot type inlet to self-start at the Mach number value calculated previously (Mach number at the cowl entrance). This simplified criterion, which has been used successfuly in previous two-dimensional optimizations[18] has been chosen to avoid an additional costly flow field calculation. During all optimizations, the inlet was required to be self-started at Mach 2.2.

Constraint on the Mass Flow Rate

In the present optimizations the mass flow rate acted as a constraint through two different ways. Since the inlet has to be adapted to a given engine, the mass flow captured by the inlet is required to be large enough to feed this engine. A constraint is consequently applied on the mass flow rate crossing the inlet. The mass flow rate was required to be larger than a specified and stage-dependent value for each stage of the mission, for the candidate inlet to be considered of interest.

To prevent the mass-flow rate constraint to be re-

spected by simply increasing the height of the cowl (scaling effect), a constraint on the mass flow rate coefficient, ε has been added. The mass flow rate coefficient was also required to be larger than a specified and stage-dependent value.

The following table summarizes the constraints related to the mass flow rate which have been considered during the optimizations:

Flight Condition	Accel.	Cruise	Maneu.
Min. MFR	1.6 kg/s	1.4 kg/s	2 kg/s
Min. ε	0.85	0.95	0.8

Table 4 Mass flow rate constraints for the different mission stages

4.2.3 GADO settings

Based on the experience gained during the previous inlet optimizations[8,19] the following settings have been used for the optimizer GADO:

Run	#iter.	Working Pop.	Stored Pop.	Random seed
Cruise	2000	50	2000	45
Mission	2200	50	2000	47

Table 5 GADO settings for the two optimizations

4.3 Analysis of the Results for the Single-Flight-Condition Optimization (Cruise Optimization)

The convergence history of this first optimization is presented in Figure 8. This graph shows that a total pressure recovery of $\eta = 0.45$ is quickly reached by GADO, during the first 100 iterations. The main difficulty encountered by the optimizer during the early stage of the search is actually to find feasible points. Once this first step is accomplished, GADO explores the "feasible" part of the design space by searching around each new best design it finds. This search process yields several flat zones for η in the history curve. Each of these flat zone corresponds roughly to the exploration of new regions in the design space, related to different families of good designs. The notion of family is used to denote groups of designs which have designs parameters close one to another and also close values for the objective function.

Finally the optimal inlet design found by GADO is $\eta_{opt-cruise} = 0.554$. According to the shape of the optimization history curve in Figure 8, the GADO search can be considered as "converged", proving that the 2000 iterations which have been allotted to GADO were sufficient. No reseeding of the working population was performed during this GADO run.

The shape of the optimal inlet for cruise found by GADO is presented in Figure 9.

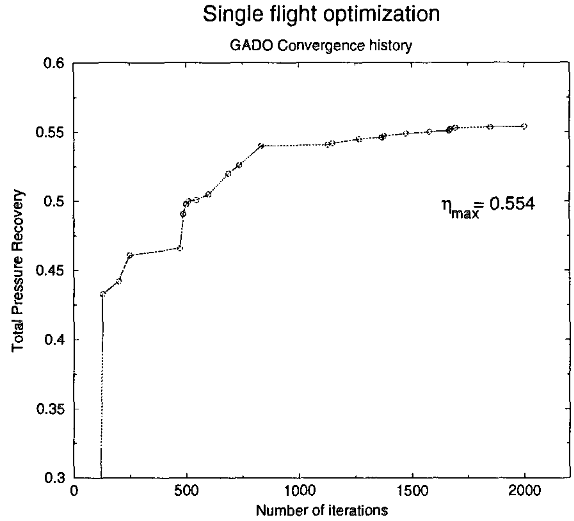

Fig. 8 GADO convergence history for the cruise optimization

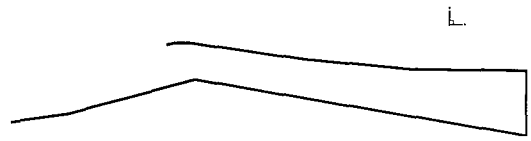

Fig. 9 Optimal design for cruise

Table 6 summarizes the performance of the optimal inlet found during the cruize optimization.

Inlet optimized for	Cruise
η_{2es3d}	0.554
$Massflow\ rate_{2es3d}$	1.911 kg s^{-1}
ε_{2es3d}	1.131

Table 6 Summary of the aerodynamic performance of the optimal inlet for the cruise phase

The performance of the optimal inlet design for cruise has finally been assessed in the two other flight-conditions of the mission, *i.e.,* for the acceleration and maneuver stage. These two computations have been performed using 2ES3D. The results are available in Table 8 (Section § 4.5) .

4.4 Analysis of the Results for the Multi-Flight-Conditions Optimization (Mission Optimization)

The convergence history of the mission optimization is presented in Figure 10. As for the cruise optimization, GADO, after having found the first "feasible" designs, quickly decreases the value of the objective function below 0.03 (See Section §4.2.1). Then the convergence history of the search presents several plateaus, corresponding roughly to the exploration of new-discovered good regions by GADO. Finally, GADO converges to a value of 0.018015 for the objective function. As presented on the Figure 10, the level of 0.0272, which is the value of the mission objective function calculated

for the optimized inlet for cruise is quickly reached and widely overcome by GADO during the mission optimization.

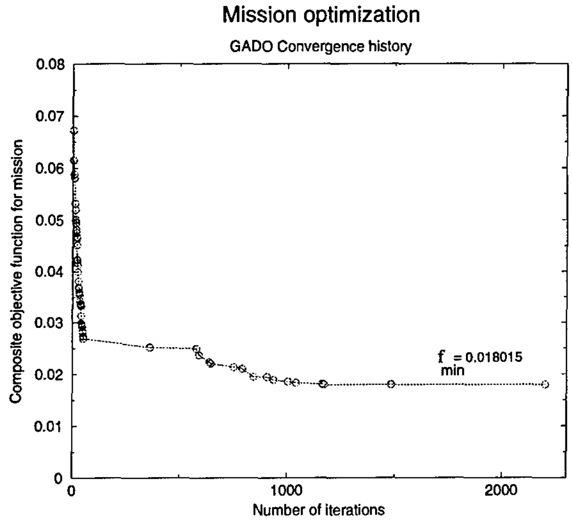

Fig. 10 GADO convergence history for the mission optimization

The shape of the optimal inlet for mission found by GADO is presented in Figure 11.

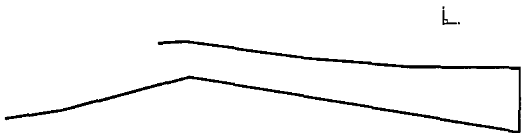

Fig. 11 Optimal design for mission

Table 7 summarizes the performance of the optimal inlet for the mission, in each of its flight condition.

Opti. Inlet for the mission	Accele.	Cruise	Maneu.
η_{2es3d}	0.714	0.552	0.644
Mass flow $rate_{2es3d}$ (in $kg \cdot s^{-1}$)	1.924	1.884	3.046
ε_{2es3d}	0.874	1.132	0.928

Table 7 Summary of the aerodynamic performance of the optimal inlet for the entire mission

4.5 Comparison Between the Two Optimizations

As it can be seen on Figure 12, or in Table 8, the inlet optimized for cruise performed essentially the same at the cruise condition as the inlet optimized for the mission: $\eta = 0.554$ versus $\eta = 0.552$. Nevertheless, the inlet optimized for the entire mission performed better on the two other flight conditions than the inlet optimized only for the cruise. According to the accuracy of 2ES3D, estimated at 5%, the differences of performance between the two optimal inlet designs are not significant for the cruise stage (where they differ by 0.4%) or acceleration stage (where they differ by 2.6%); however, there is a significant difference in performance for the maneuver stage (where they differ by 6.1%). This results reveals that the negligible improvement achieved by GADO in the cruise optimization (0.554 to be compared to 0.552) resulted in a degradation of the performance for the maneuver stage of the mission. This demonstrates the benefits of taking into account the entire mission during the optimization.

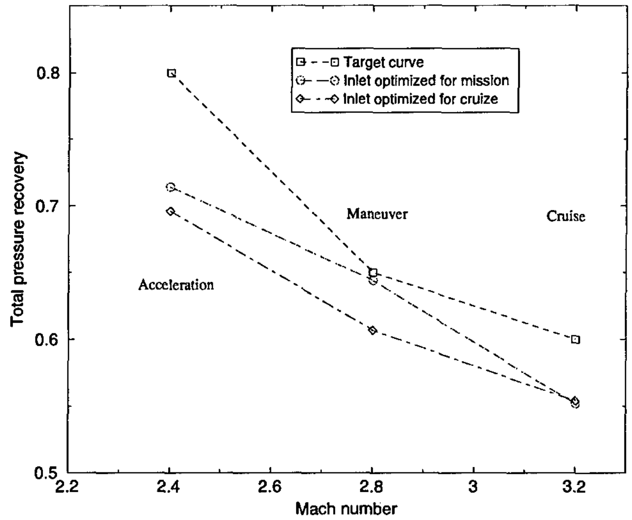

Fig. 12 Comparison between the total pressure recovery achieved by both optima over the three mission stages

Opti. Inlet	Accele.	Cruise	Maneu.
For cruise	0.696	0.554	0.607
For mission	0.714	0.552	0.644
Discrepency	2.6%	0.4%	6.1%

Table 8 Total Pressure recovery of the two optimal inlet designs for the different mission stages, estimated with 2ES3D

Figures 9 and 11 show that the two optimized inlet designs are very close the one to the other. The main difference occurs on the cowl shape for which an enlarged view is shown in Figure 13. This proves the importance of the precision with which the inlet cowl is defined, demonstrating the benefits of a finely parametrized shape of the cowl.

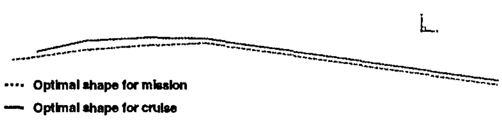

Fig. 13 Comparison of the cowl shape of the two optimized inlets

5 Conclusion and Perspectives

An automated optimal design process, coupling a stochastic optimizer and a three dimensional simulation tool, has been developed. A multi-flight-conditions optimization of a three-dimensional super-

sonic inlet has been successfully performed, demonstrating the benefits of taking into account the entire mission, rather than a single-flight condition. Compared to the human decision based design cycle currently used in industries, this innovative optimization strategy allows to investigate a larger number of configurations, while looking for maximum aerodynamic performance of the inlet under specific constraints. The use of artificial intelligence techniques guides the search process toward high interest regions of the design space, minimizing the number of computations required to reach a high performance level. The results of the optimizations performed during this study indicate that automated optimal design strategies are very well suited to this kind of critical design problems.

The optimization process presented in this paper has reached the point where industrial application can now be envisaged. The simulation part can address the highly three-dimensional geometries of the most complex industrial problems. The physical modeling used for performance evaluation has proved to be robust and computationally efficient. Current efforts are focused on validation of the inlet designs using RANS simulations.

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Statement of No Restriction

The authors declare that there is no restriction on the presentation and publication of the present paper.

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DISCUSSION

Session IV, Paper #30

Prof J Hauser (CLE, Germany) asked what advantage there was using Genetic Algorithm rather than Simulated Annealing.

> **Prof Knight** suggested that GAs were more robust in that they did not depend on a valid initial configuration whereas simulated annealing can be sensitive to the initial "temperature", the proper setting of which is experience dependent.

Prof Hauser asked whether the GA could be accelerated by combining it with a deterministic method.

> **Prof Knight** believed that a GA in its later stages of evolution demonstrates some kind of deterministic behaviour, although in general quadratic convergence is not achieved.